Dark matter bound states, scalar mediators and the Higgs

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CosmoChart
Horizon 2020, grant agreement No 101002846

Scalars 2023
Warsaw, 14/09/2023

Frontiers in particle dark matter searches

(very simplistic summary)

Past decades

Most research focused on

$\mathbf{m_{DM} \sim 100\ GeV \sim m_{W,Z}}$

(e.g. prototypical WIMP scenario)

Current frontiers

Heavy dark matter

$\mathbf{m_{DM} \gtrsim TeV}$

Not constrained by colliders.

→ Experimentally probed by existing / upcoming **telescopes** e.g. HESS, IceCube, CTA, Antares

Light dark matter

$\mathbf{m_{DM} \lesssim few\ GeV}$

Not constrained by older direct detection experiments

→ Development of new generation of **direct detection** experiments

Heavy ($m_{DM} \gtrsim$ TeV) dark matter

How does the phenomenology of dark matter look like?
(in popular scenarios, e.g. thermal-relic DM)

New type of dynamics emerges:
Long-range interactions

$$\lambda_B \sim \frac{1}{\mu v_{\rm rel}}, \frac{1}{\mu\alpha} \lesssim \frac{1}{m_{\rm mediator}} \sim \text{interaction range}$$

μ: reduced mass $(m_{\rm DM}/2)$

Heavy (m … TeV

Does this occur in models we care about?

- WIMPs with m > few TeV
- WIMPs with m < TeV co-annihilating with coloured/charged particles
- Self-interacting DM

not so heavy DM!

… typ… …erges:

L… interactions

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μ: reduced mass ($m_{\rm DM}/2$)

What changes when the interactions are long-ranged?

Implications of non-perturbative effects

Distortion of scattering-state wavefunctions
⇒ affects all cross-sections
e.g. annihilation, elastic scattering

- Production in early universe, e.g. freeze-out
  ⇒ changes correlation of parameters (mass – couplings)
- Indirect detection signals
- Elastic scattering

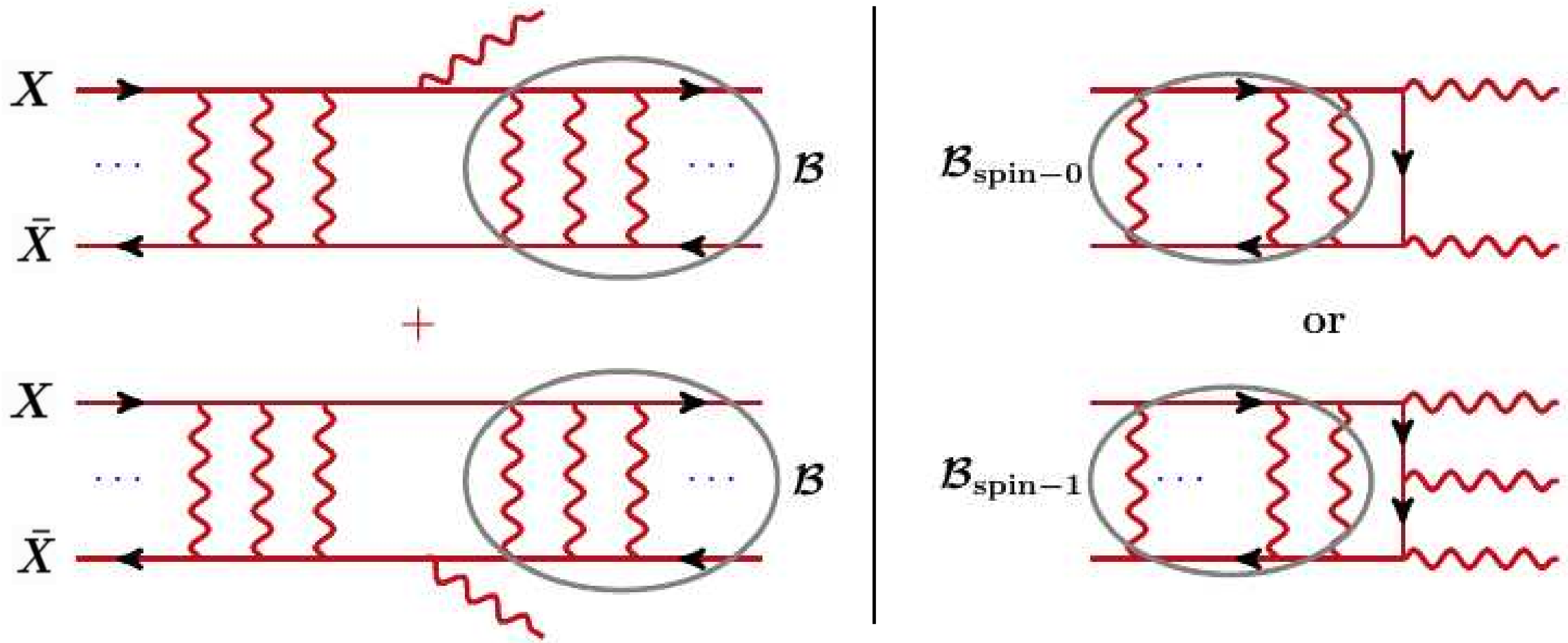
Unstable bound states (positronium-like)
⇒ extra annihilation channel

- Production in early universe, e.g. freeze-out **von Harling, Petraki 1407.7874**
- Indirect detection
- Novel low-energy indirect detection signals
- Colliders

Stable bound states

- Elastic scattering (usually screening)
- Novel low-energy indirect detection signals
- Inelastic scattering in direct detection experiments (?)

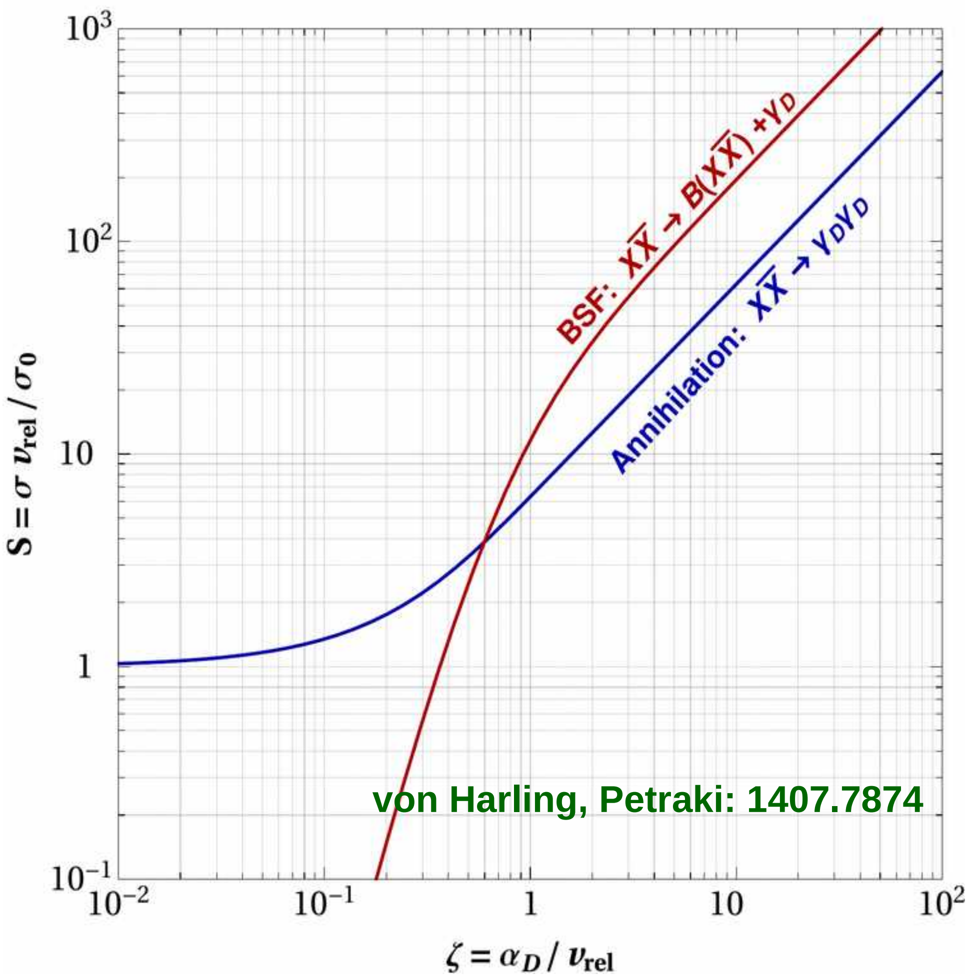
Radiative bound-state formation and decay



Opens a new annihilation channel !

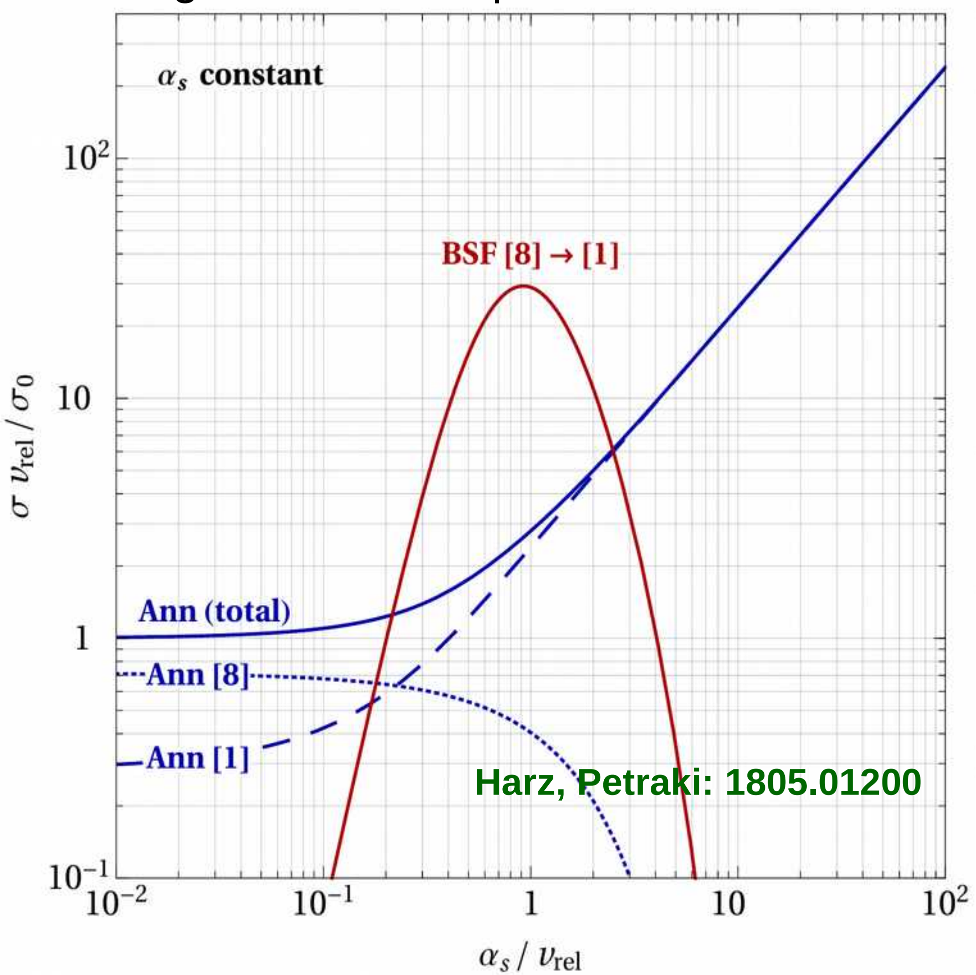
Annihilation vs Bound State Formation

U(1) model



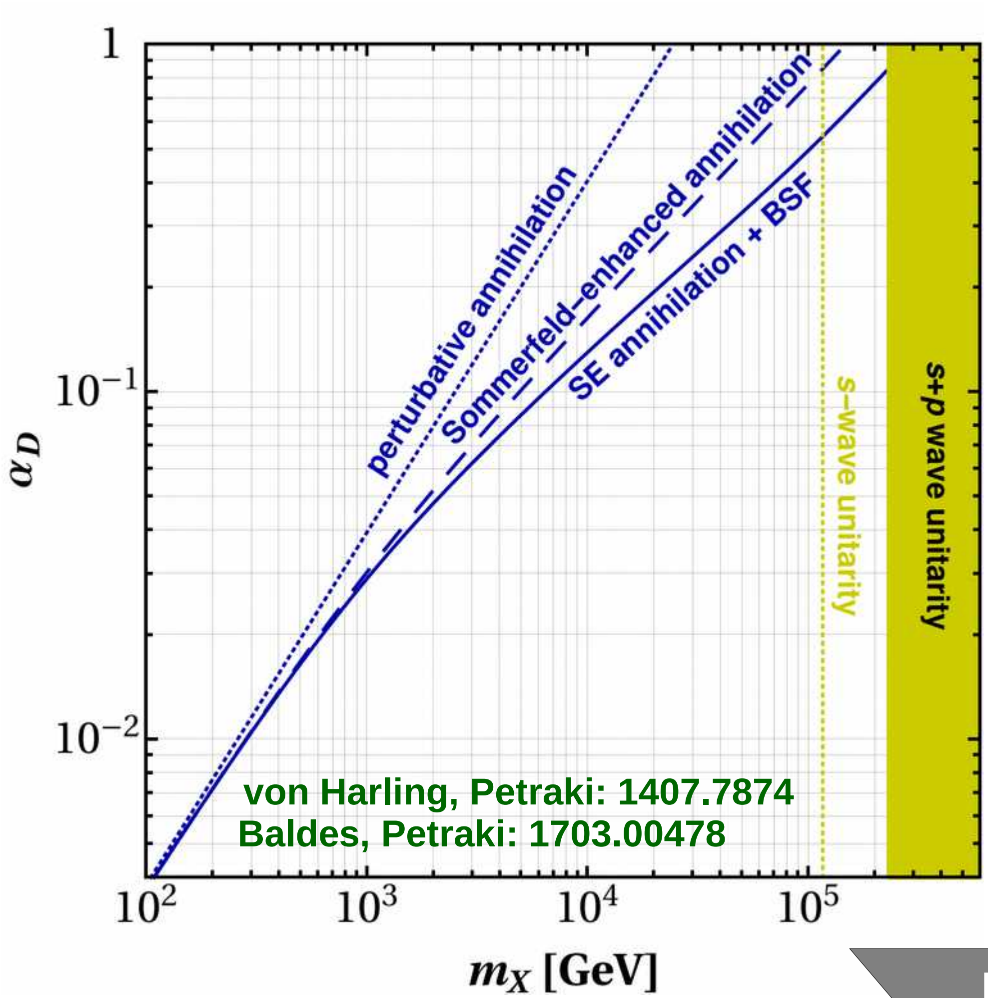
SU(3) model

e.g. neutralino-squark coann in SUSY



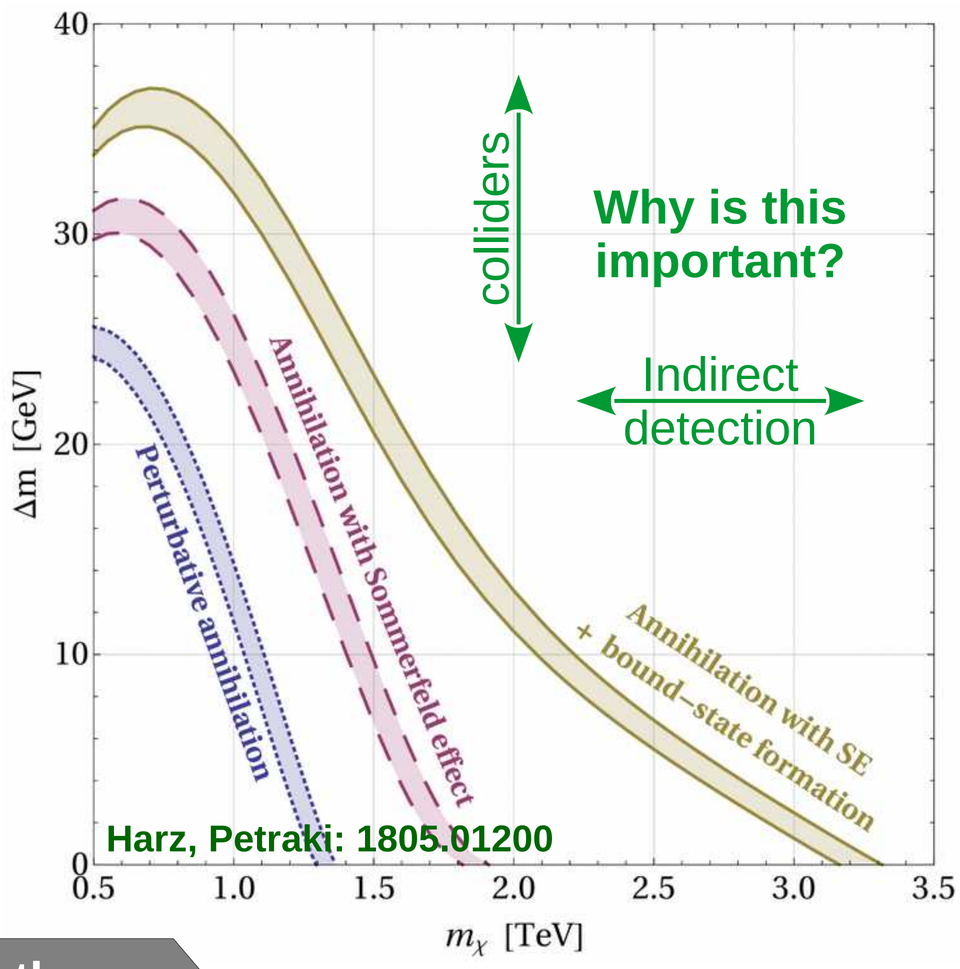
Annihilation vs Bound State Formation

U(1) model



SU(3) model

neutralino-squark coann in SUSY



Not the final picture!

Scalars 2023

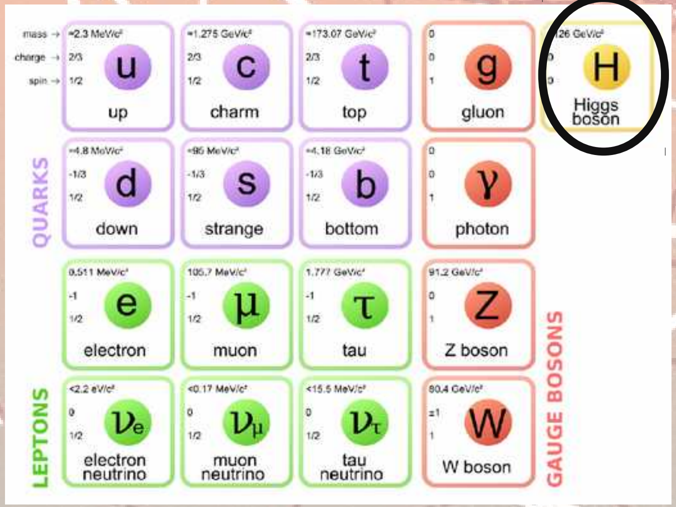
An opportunity to discuss various aspects of scalar particles.

13-16 September 2023
Warsaw (Ochota Campus)

scalars2023.fuw.edu.pl

What about light <u>scalar</u> mediators?
And why do we care?

Hidden sector models, e.g. self-interacting DM



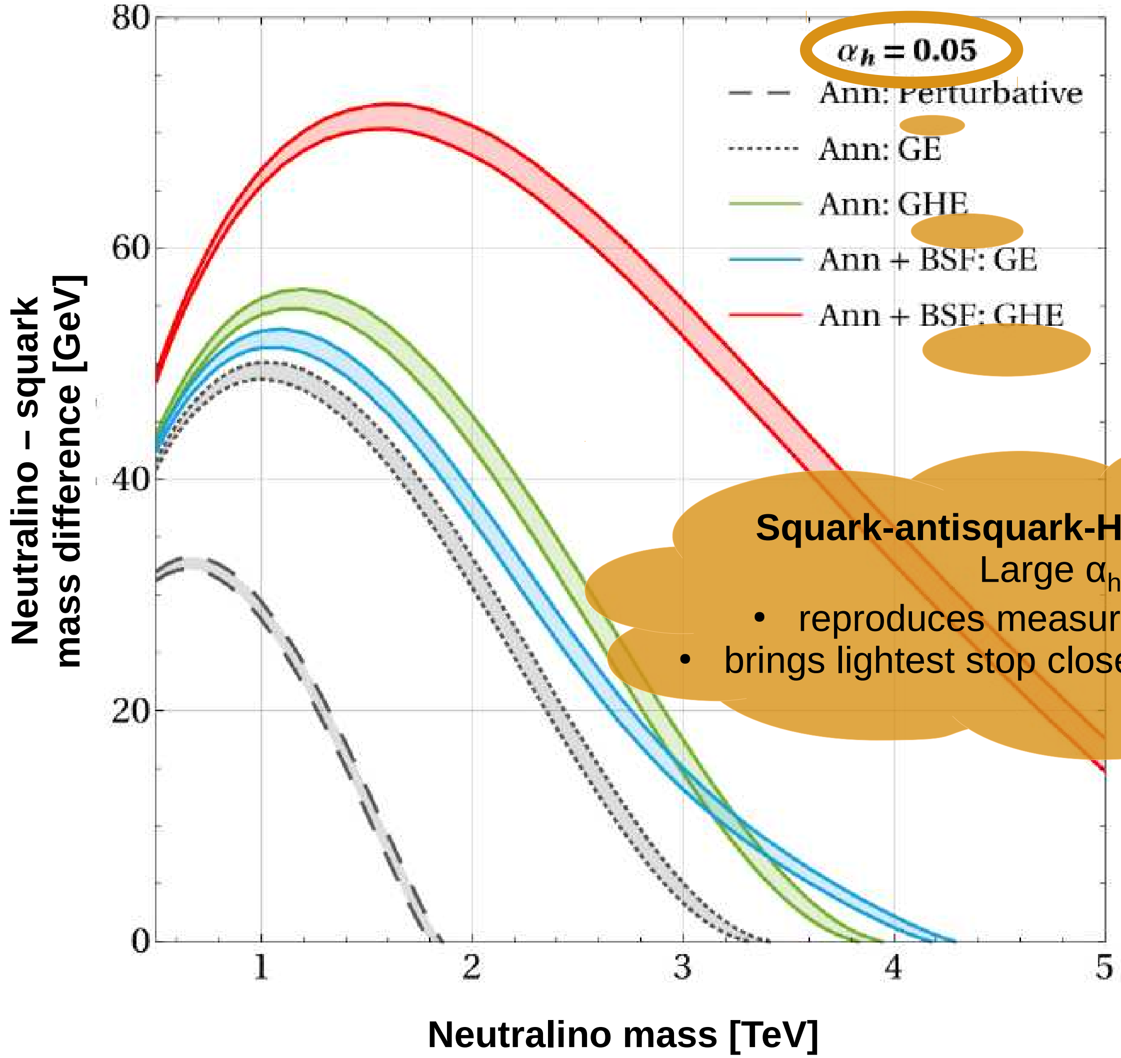
What do *light* force mediators do?

- Generate potential → Sommerfeld effect, bound states.
- Provide channel for transitions via on/off-shell emission. Spin of the emitted mediator determines selection rules.

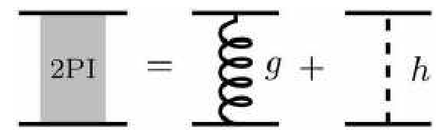
In many realistic models, including WIMPs:
several mediators present

DM coannihilation with scalar colour triplet

The effect of the Higgs-mediated potential



Squark-antisquark-Higgs coupling
Large α_h
- reproduces measured Higgs mass
- brings lightest stop close in mass with LSP



$$V(r) = -\frac{\alpha_g}{r} - \frac{\alpha_h}{r} e^{-m_h r}$$

Gluon exchange **Higgs exchange**

Not the final picture!

Harz, Petraki: 1711.03552, 1901.10030

Bound-state formation via emission of a light scalar

- Capture via emission of neutral scalar suppressed, due to selection rules: quadruple transitions

March-Russel, West 0812.0559
Petraki, Postma, Wiechers: 1505.00109
An, Wise, Zhang: 1606.02305
Petraki, Postma, de Vries: 1611.01394

- Capture via emission of charged scalar [or its Goldstone mode] extremely rapid: monopole transitions !

Ko, Matsui,Tang: 1910:04311
Oncala, Petraki: 1911.02605
Oncala, Petraki: 2101.08666
Oncala, Petraki: 2101.08667

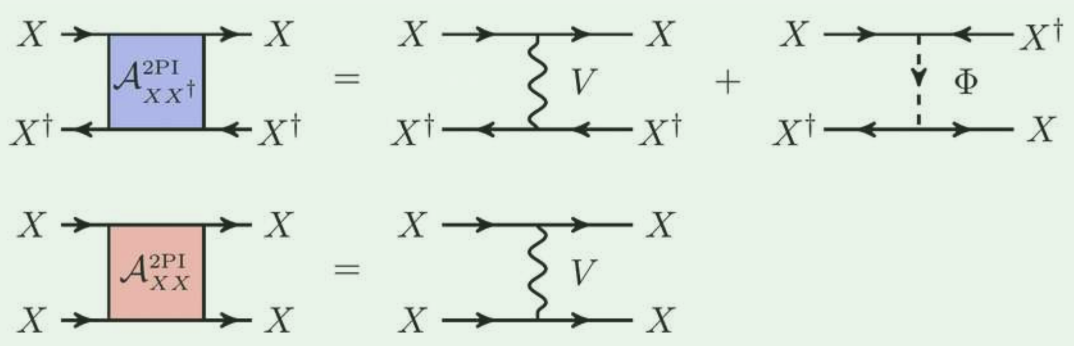
Sudden change in effective Hamiltonian precipitates transitions. Akin to atomic transitions precipitated by β decay of nucleus.

Bound-state formation
via emission of a charged scalar

Scalar DM *X,X†* coupled to doubly charged light scalar mediator *Φ*

$$\mathcal{L} \supset \; -igX^\dagger V^\mu(\partial_\mu X) \; - i2g\Phi^\dagger V^\mu(\partial_\mu \Phi) \; - \frac{y m_X}{2} X X \Phi^\dagger + h.c.$$

$$m_X \gg m_\Phi$$



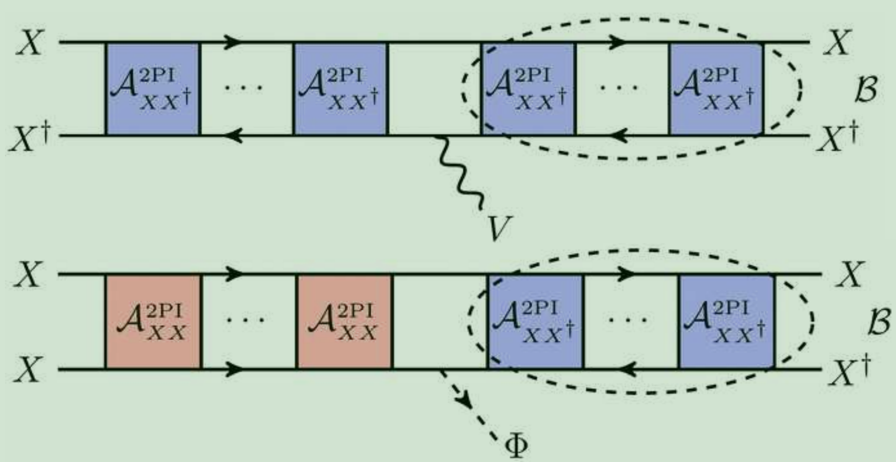
$$U_{XX^\dagger}(r) \; = \; -\frac{\alpha_V}{r} \; - (-1)^\ell \, \frac{\alpha_\Phi}{r} \, e^{-m_\Phi r}$$

$$U_{XX}(r) \; = \; +\frac{\alpha_V}{r}$$

Potential differs even in the global symmetry limit $\alpha_V \to 0$

BSF$_V$

BSF$_\Phi$



dipole transition

$$\mathcal{M} \sim 2g \int d^3p \; \psi^*_{n\ell m}(\mathbf{r}) \nabla \phi_{\mathbf{k}}(\mathbf{r}) \sim 2g \int d^3p \; \psi^*_{n\ell m}(\mathbf{r}) \mathbf{r} \phi_{\mathbf{k}}(\mathbf{r})$$

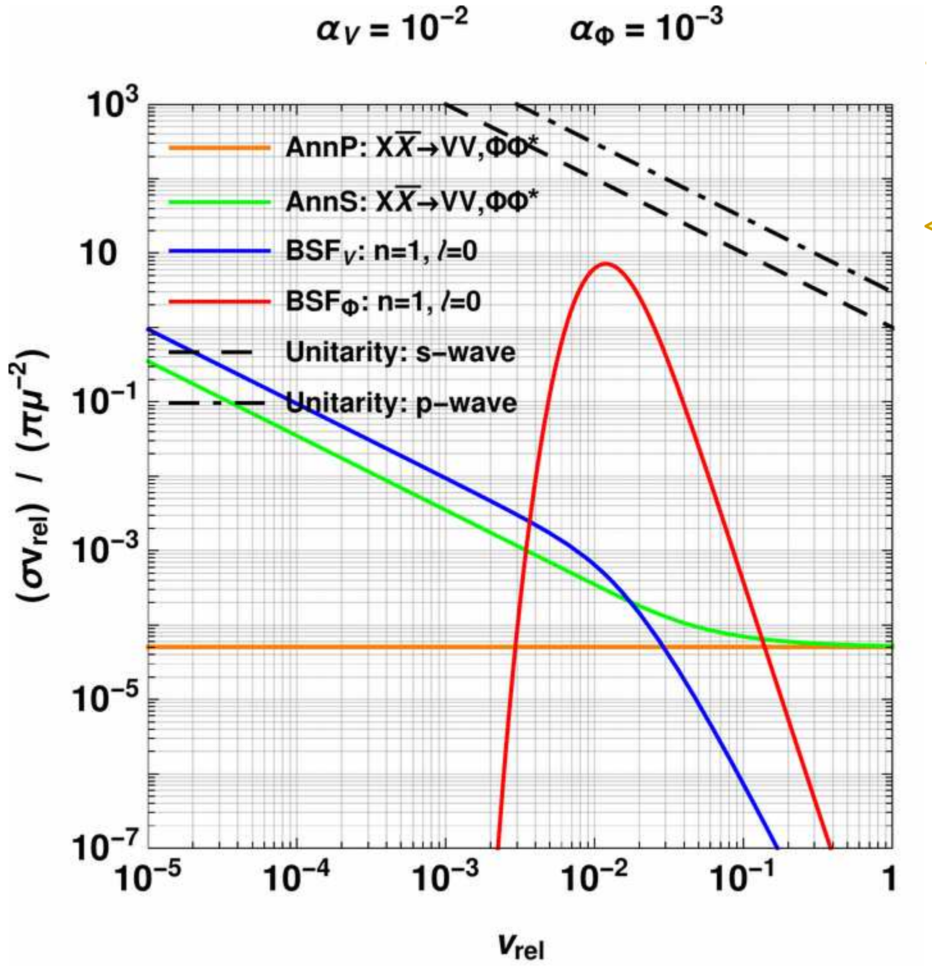
Change in effective Hamiltonian ⇒ monopole transition

$$\mathcal{M} \sim 2y \int d^3p \; \psi^*_{n\ell m}(\mathbf{r}) \; \phi_{\mathbf{k}}(\mathbf{r})$$

extremely fast!

Oncala, KP: 1911.02605

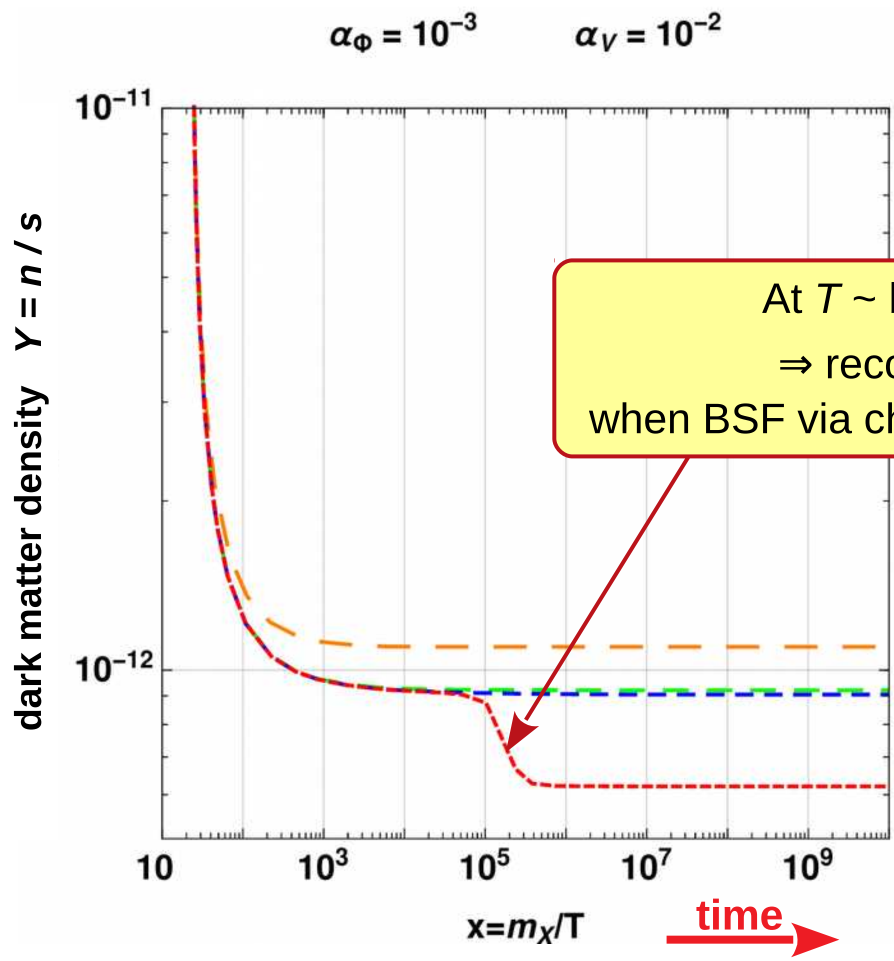
Scalar DM $X, X^\dagger$ coupled to doubly charged light scalar mediator Φ



BSF$_\Phi$ very large, even for small values of α_Φ, α_V !

Oncala, KP: 1911.02605

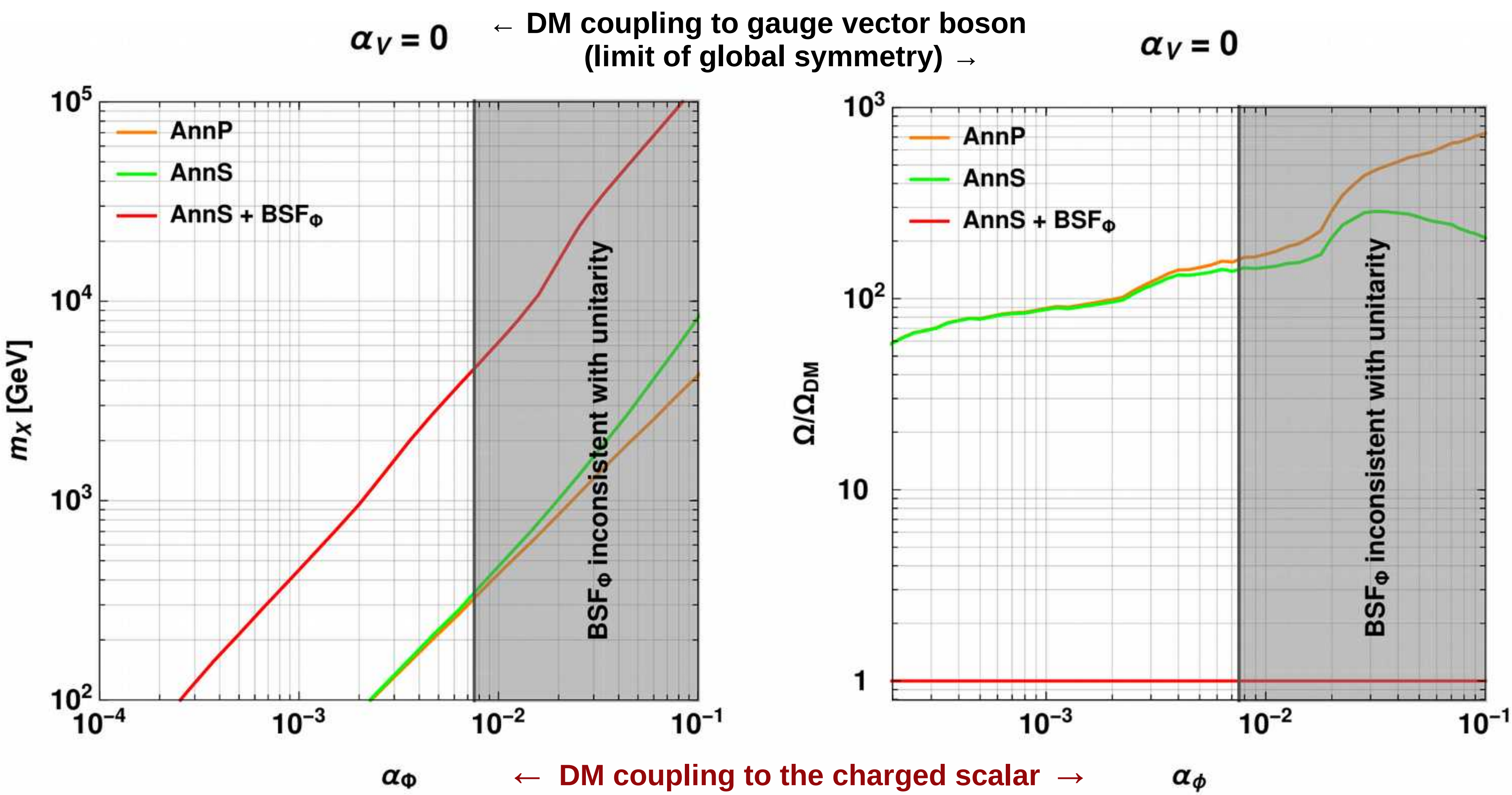
Scalar DM $X, X^\dagger$ coupled to doubly charged light scalar mediator Φ



At T ~ binding energy << m_X /30
⇒ recoupling of DM destruction
when BSF via charged scalar emission considered

Oncala, KP: 1911.02605
(see also Ko,Matsui,Tang:1910:04311)

Scalar DM $X, X^\dagger$ coupled to doubly charged light scalar mediator Φ

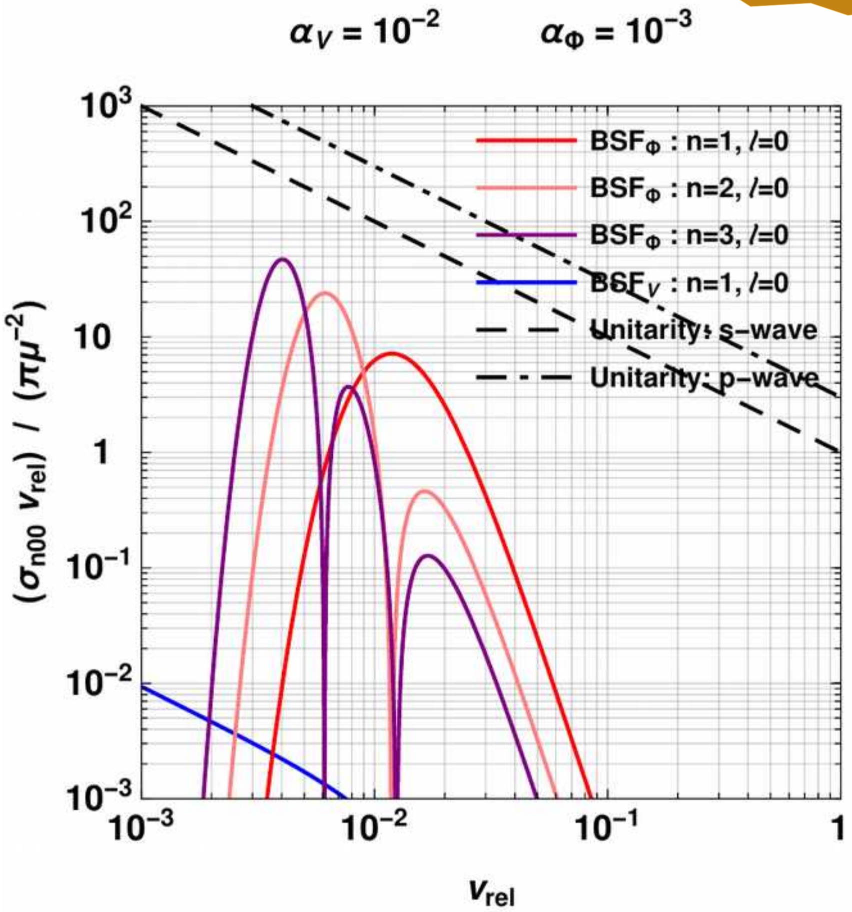


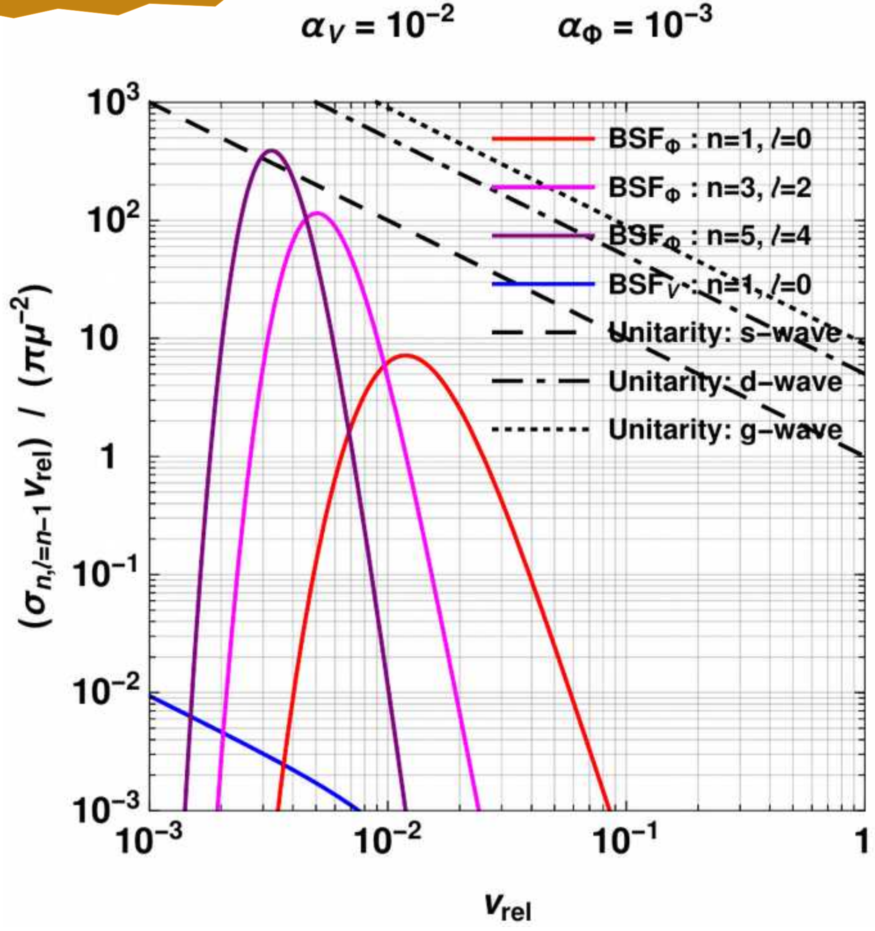
Oncala, Petraki: 1911.02605

Not the final picture!

Scalar DM $X, X^\dagger$ coupled to doubly charged light scalar mediator Φ

Capture into excited states important!





Oncala, KP: 1911.02605

Bound-state formation
via Higgs doublet emission

Renormalisable WIMP models with coupling to the Higgs

In some of the archetypal WIMP DM models,
DM is the lightest linear combination of the neutral component of SU(2) multiplets that couple to the Higgs

$$\boxed{\delta\mathcal{L} \supset -y\bar{X}_n H X_{n+1} + \mathrm{h.c.}}$$

Trilinear Higgs doublet-DM-DM, independent of Higgs VEV

Includes many supersymmetric scenarios,
e.g. Wino-Higgsino, coloured co-annihilation

If m > 5 TeV, DM freeze-out begins before electroweak phase transition.

Doublet-Singlet coupled to the Higgs

$$\delta\mathcal{L} = \frac{1}{2}\bar{S}(i\partial\!\!\!/ - m_S)S + \bar{D}(i D\!\!\!\!/ - m_D)D - (y_L \bar{D}_L H S + y_R \bar{D}_R H S) + \text{h.c.}$$

for simplicity, set: $\quad y_L = y_R \equiv y, \qquad m_S = m_D \equiv m$

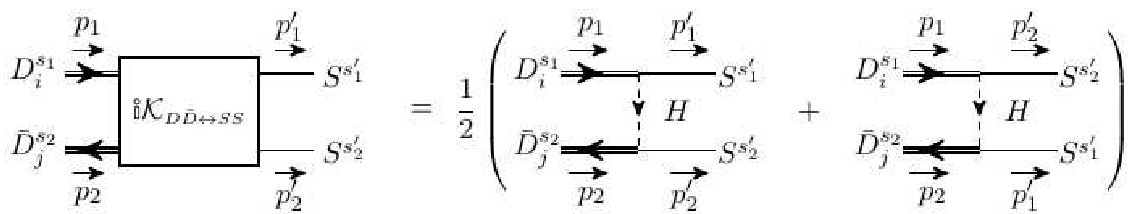
field	$SU_L(2)$	$U_Y(1)$	$\mathbb{Z}_2$
S	1	0	-1
D	2	$1/2$	-1
H	2	$1/2$	$+1$

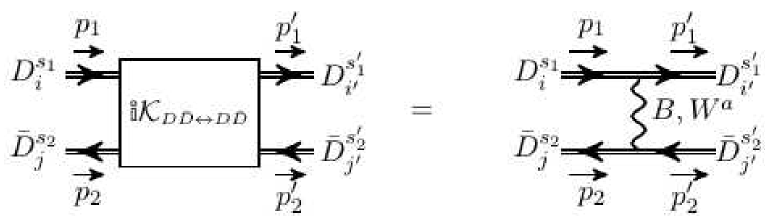
Calculate all cross-sections and freeze-out in the symmetric electroweak phase.

Oncala, KP: 2101.08666/7

Doublet-Singlet coupled to the Higgs

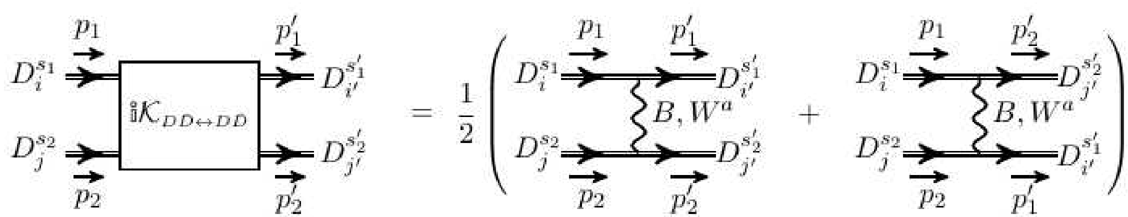
Non-relativistic potentials





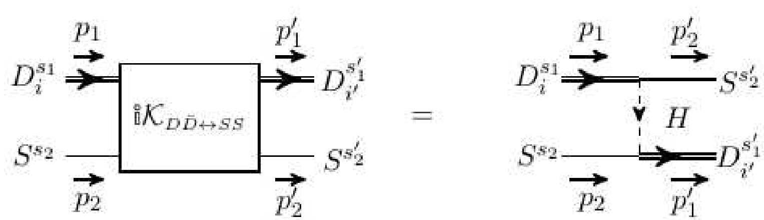
Need to project on
- gauge,
- spin,
- orbital angular momentum

eigenstates



Neglect (T-dependent) H mass in the potential

but consider it in phase-space suppression for BSF via H emission ($\rightarrow$ analytical cross-sections)



Oncala, KP: 2101.08666/7

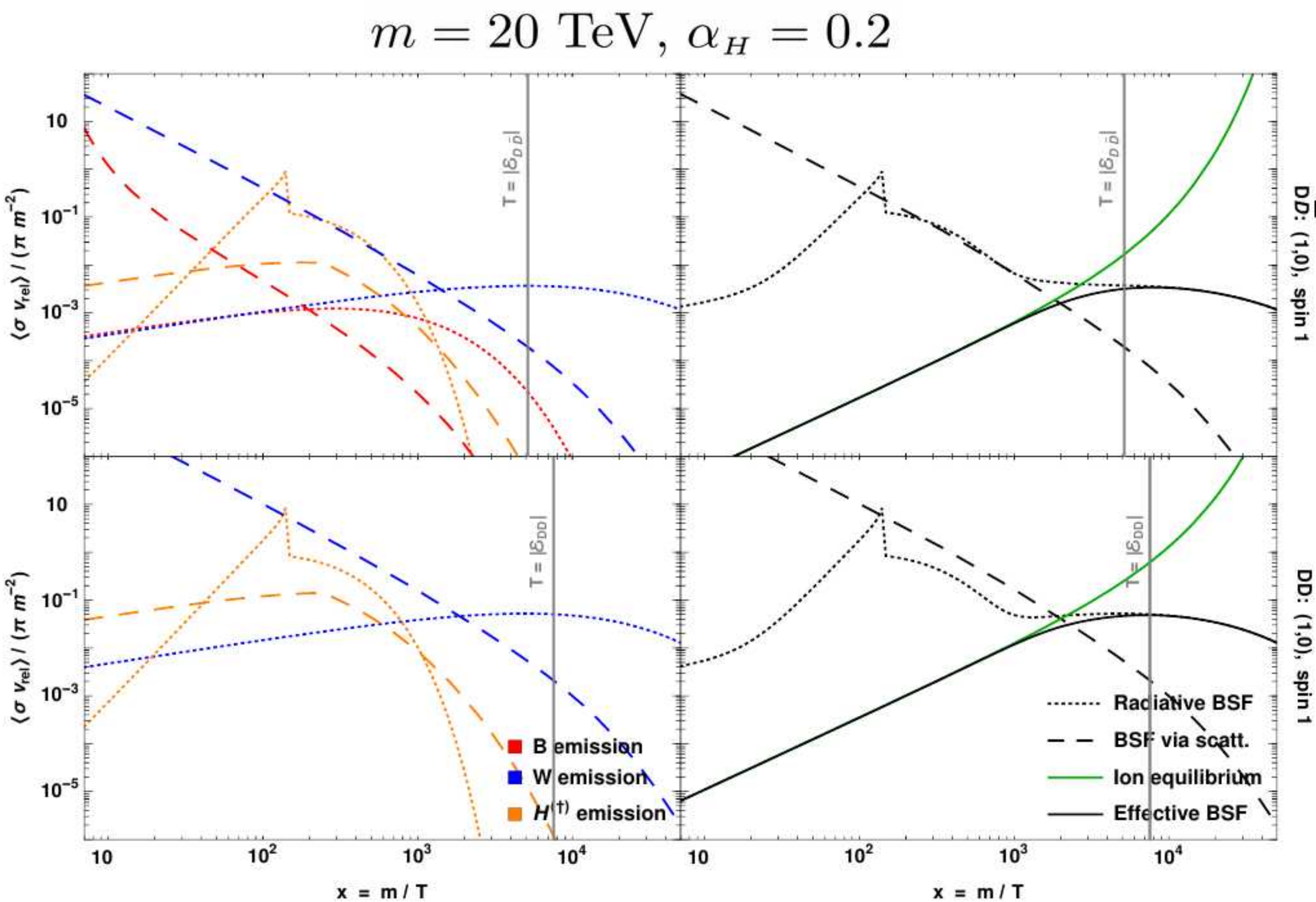
Doublet-Singlet coupled to the Higgs

Bound-state species (n=0, ℓ=0)

Bound state ($\mathcal{B}$)	$U_Y(1)$	$SU_L(2)$	Spin	dof (g_B)	Bohr momentum ($\kappa_{\mathcal{B}}$)	Decay rate (Γ_B)
$SS/D\bar{D}$	0	$\mathbb{1}$	0	1	$\frac{m\alpha_A}{2}$	$\frac{m\alpha_A^3(\alpha_1^2+3\alpha_2^2)}{16}\left(\frac{\alpha_A}{\alpha_A+\alpha_R}\right)$
$D\bar{D}$	0	$\mathbb{1}$	1	3	$\frac{m(\alpha_1+3\alpha_2)}{8}$	$\frac{m(\alpha_1+3\alpha_2)^3[(\alpha_1+2\alpha_H)^2+40\alpha_1^2]}{2^{11}\cdot 3}$
DD	1	$\mathbb{1}$	1	3	$\frac{m(-\alpha_1+3\alpha_2)}{8}$	$\frac{m(-\alpha_1+3\alpha_2)^3\alpha_H^2}{2^7\cdot 3}$
DS	1/2	$\mathbb{2}$	0	2	$\frac{m\alpha_H}{2}$	Transition to $\mathcal{B}(SS/D\bar{D})$:

Doublet-Singlet coupled to the Higgs

Bound-state formation cross-sections



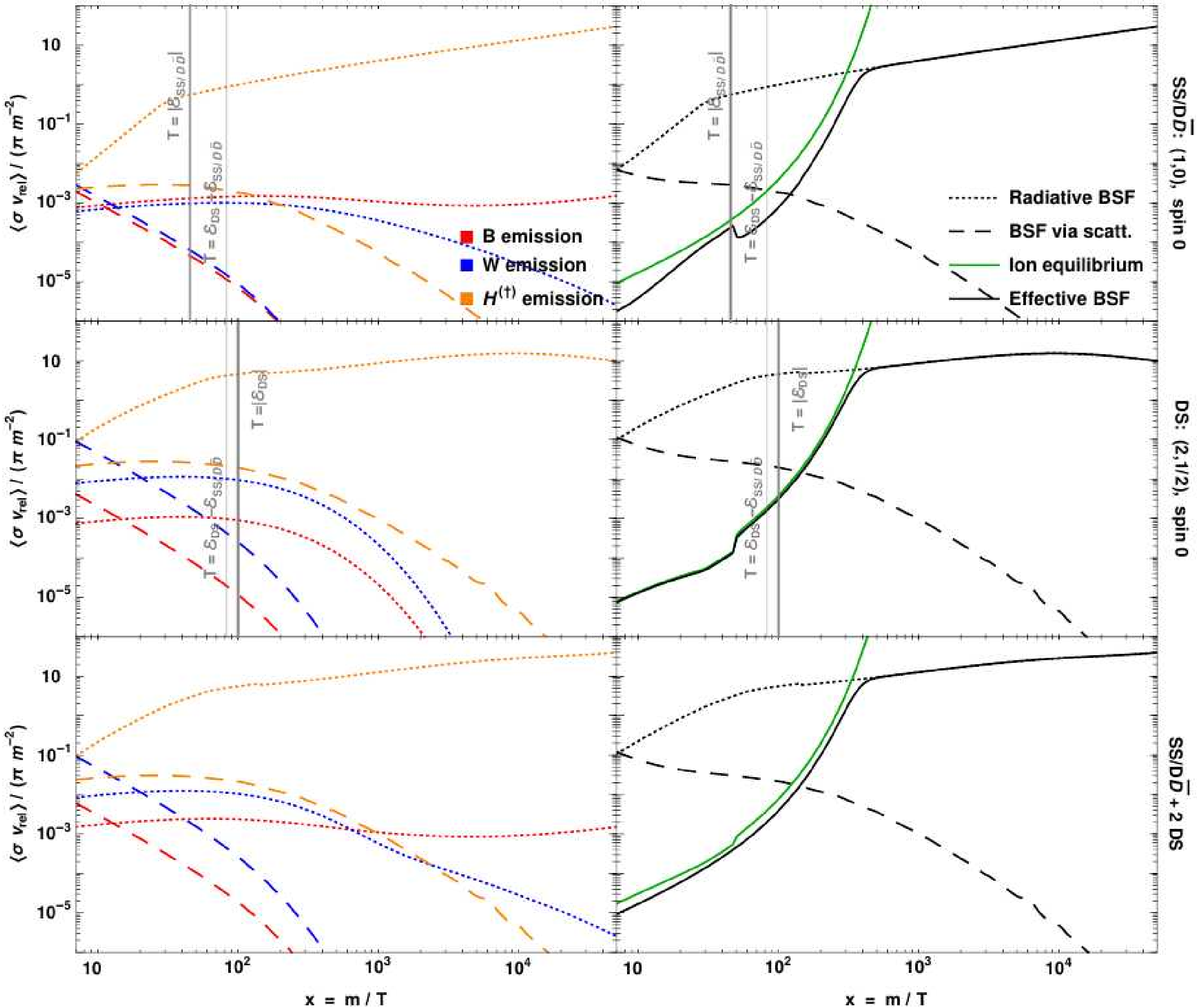
- BSF via scattering on plasma has no effect
- Departure from ionisation equilibrium at T > binding energy

Oncala, KP: 2101.08666/7

Doublet-Singlet coupled to the Higgs

Bound-state formation cross-sections

$m = 20$ TeV, $\alpha_H = 0.2$



- **BSF via scattering on plasma has no effect**

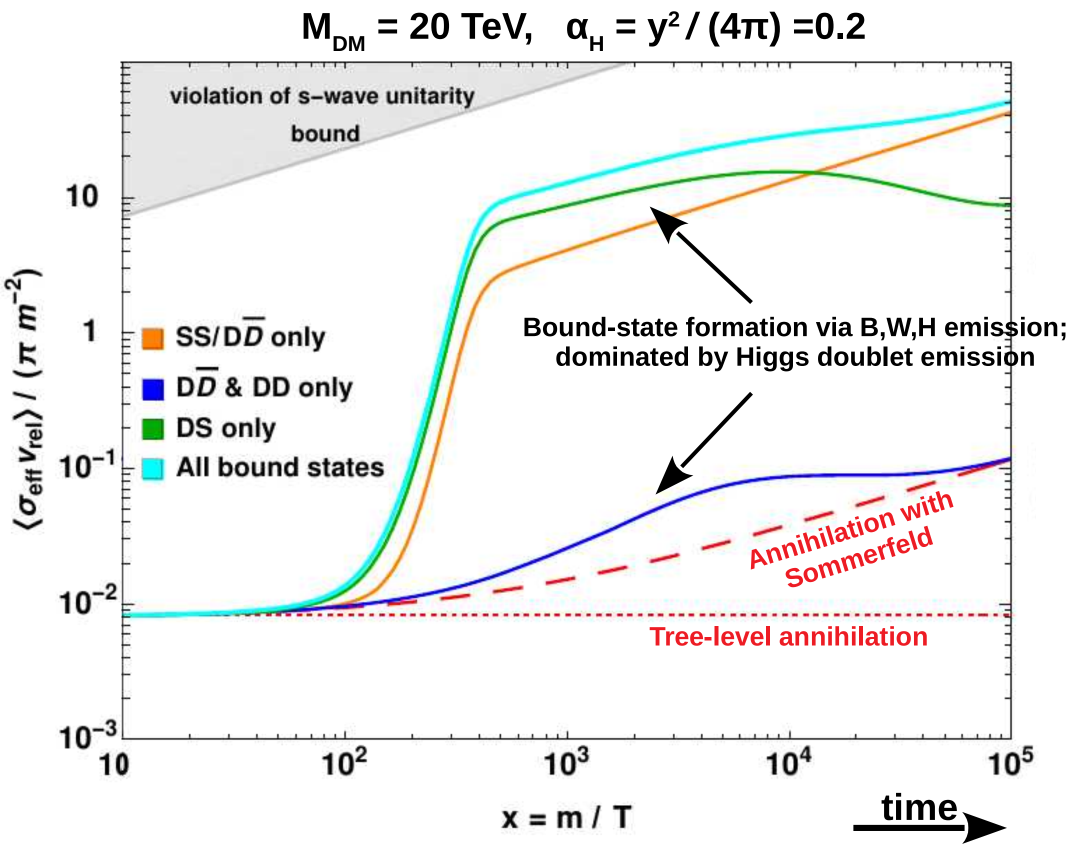
  (scattering kind of important for bound-to-bound transitions)

- **Departure from ionisation equilibrium at T << binding energy**

  (because of largeness of monopole BSF cross-sections)

Doublet-Singlet coupled to the Higgs

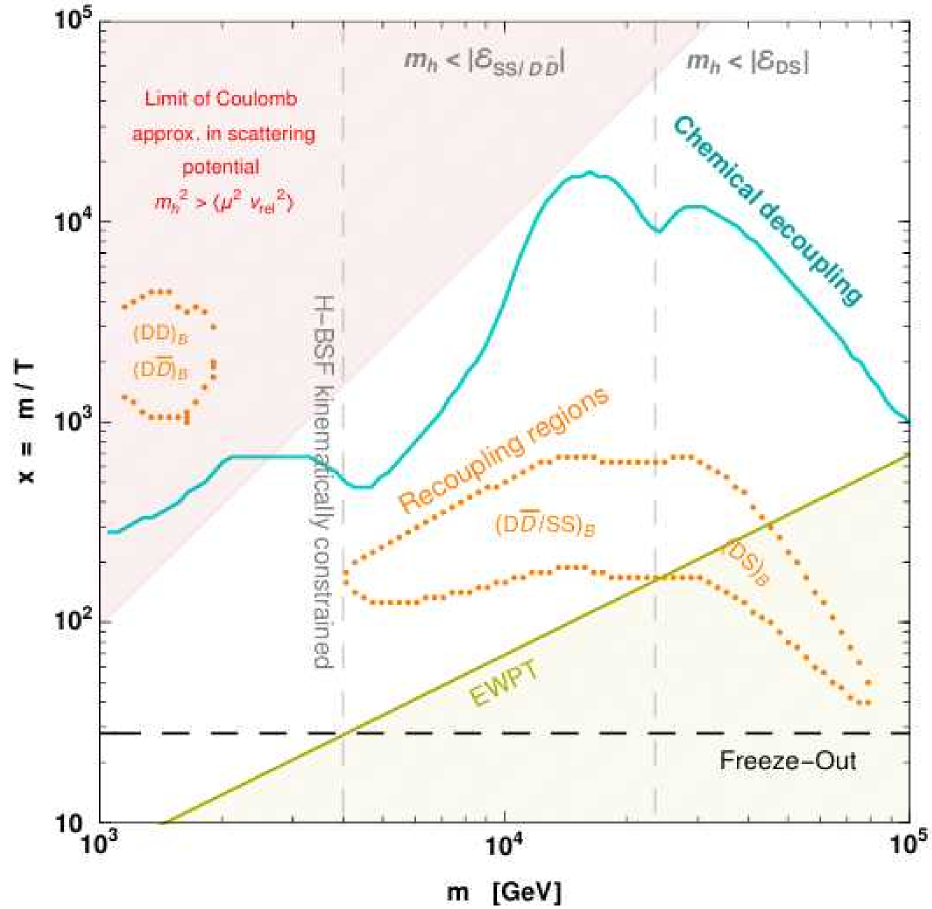
Effective cross-sections



Oncala, KP: 2101.08666/7

Doublet-Singlet coupled to the Higgs

Timeline

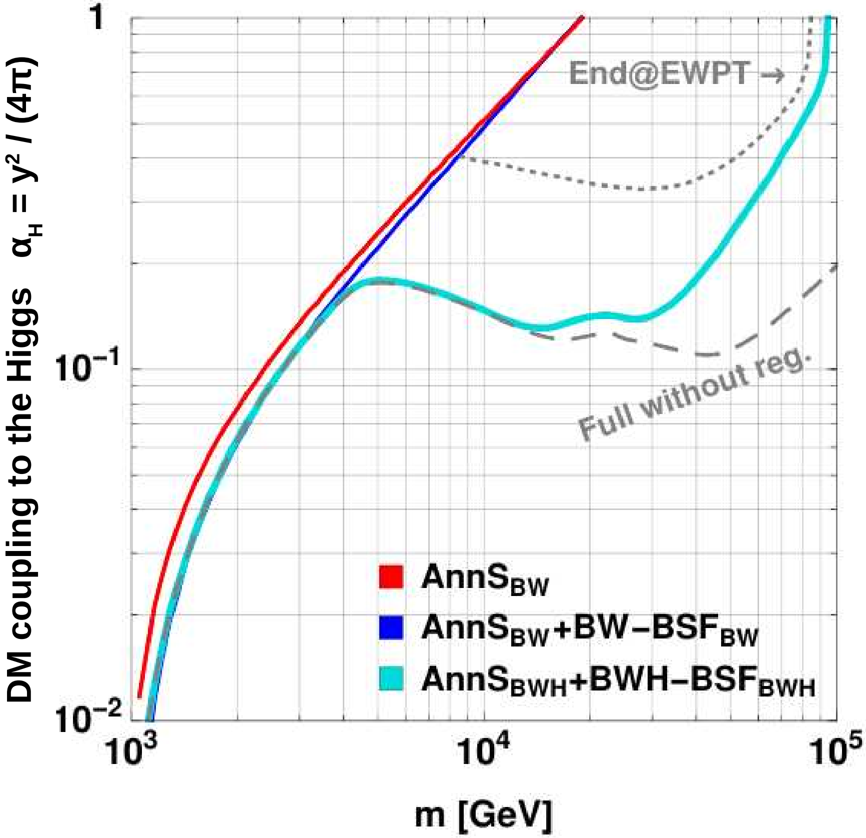


BSF via Higgs doublet emission
~ BSF via h^0, longitudinal $W^\pm$ & Z below EWPT :
Goldstone Boson equivalence theorem
Ko,Matsui,Tang:1910:04311

Oncala, KP: 2101.08666/7

Doublet-Singlet coupled to the Higgs

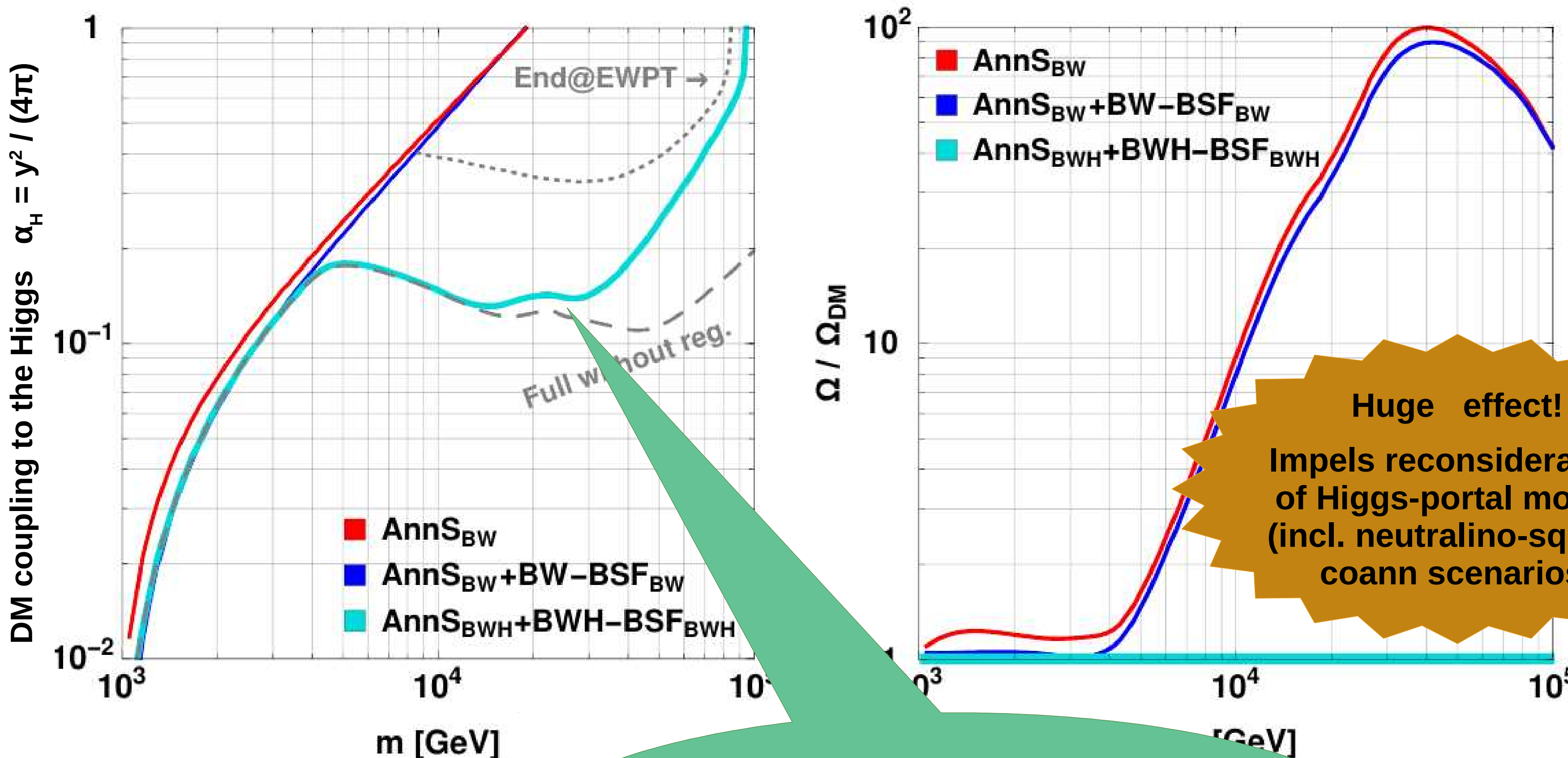
Relic density



Oncala, KP: 2101.08666/7

Doublet-Singlet coupled to the Higgs

Relic density



Huge effect!

Impels reconsideration of Higgs-portal models (incl. neutralino-squark coann scenarios)

Effect only at large α_H, due to phase-space suppression in Higgs emission.

For higher multiplets, important effect expected also at lower α_H.

Oncala, KP: 2101.08666/7

Conclusions

- **Bound states impel complete reconsideration of thermal decoupling at / above the TeV scale: *emergence of a new type of inelasticity*** **von Harling, KP: 1407.7874**

  Model-independent unitarity arguments **Baldes, KP: 1703.00478**

- **Role of the Higgs doublet or other scalars can be extremely important.**
  Ko, Matsui,Tang: 1910:04311; Oncala, KP: 1911.02605, 2101.08666, 2101.08667

- **Experimental implications:**
  - DM heavier than anticipated: multi-TeV probes very important

    ⇒ build the 100 TeV collider :)
  - Indirect detection:

    Enhanced rates due to BSF. **Cirelli, Panci, KP, Sala, Taoso: 1612.07295**
    Novel signals: low-energy radiation emitted in BSF **Baldes, Calore, KP, Poireau, Rodd: 2007.13787**
    Indirect detection of asymmetric DM **Baldes et al.: 1703.0478, 1712.07489**
  - Colliders: improved detection prospects due increased mass gap in coannihilation scenarios

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- **Effects *not* limited to freeze-out scenario:**
  freeze-in, asymmetric DM, self-interacting DM, stable bound states